

Frequency domain methods for Vibroseis deconvolution

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Summary

Traditional vibroseis seismic processing produces a bandlimited zero-phase Klauder wavelet through crosscorrelation of the sweep with the recorded signal. An alternative wavelet processing method involves deconvolving the sweep from the recorded vibroseis trace. This deconvolution can be achieved through frequency domain division. We compare and contrast the advantages and disadvantages of sweep deconvolution versus crosscorrelation on synthetic and field data.

Introduction

In vibroseis data, the recorded trace contains an embedded sweep. To resolve the data it is necessary to remove the sweep from the trace. This is traditionally completed with the use of crosscorrelation, where the sweep is crosscorrelated with the trace creating an embedded Klauder wavelet. Sheriff (1990) defines the Klauder wavelet as the autocorrelation of a linear vibroseis sweep. Sheriff's definition includes all non-linear sweeps since they are a combination of a series of linear sweeps. An additional problem encountered in vibroseis data is the mixed-phases associated with the combination of the zero-phase Klauder wavelet produced by crosscorrelation and minimum-phase attenuation. Changes occurring are associated with both the amplitudes and phase due to the linear and non-linear filter effects from the vibrator system and the waves as they propagate in the earth. The earth attenuation causes the higher frequencies to be attenuated more than the low frequencies. There is also the creation of a mixed-phase wavelet, a result of the convolution of the minimum-phase earth effects and the Klauder wavelet.

This paper examines the potential of utilizing frequency domain division to remove the sweep from the recorded trace. A comparison has been made for cross correlation and frequency domain sweep deconvolution with both synthetic and field data.

Crosscorrelation

The industry standard for removal of an embedded sweep is crosscorrelation. This method of vibroseis deconvolution utilizes the theory that the autocorrelation of a signal is equal to a spike. Autocorrelation is defined as a measure of the similarity of a waveform with a time-shifted version of itself, with the maximum occurring at zero-lag (Sheriff, 1990). The autocorrelation of a vibroseis sweep is referred to as a Klauder wavelet. When the recorded data is crosscorrelated with the sweep, the remaining data will only contain information that is common to both waveforms; therefore the method acts as a filter for unwanted frequencies. The results of crosscorrelation are extremely sensitive to changes in the sweep. Errors associated with the sweep can be partially attributed to attenuation and improper vibration (Ristow and Jurczyk, 1975).

The basic seismic convolutional model for a vibroseis source is

$$x(t) = r(t) * s(t), \quad (1)$$

where $x(t)$ is the recorded trace, $r(t)$ is the geological reflectivity, $s(t)$ is the sweep and $*$ is the convolution operator. To remove the sweep, the trace is crosscorrelated (\otimes) with the sweep. The equation for the deconvolved sweep is

$$cc(t) = r(t) * s(t) \otimes \overline{s(t)}, \quad (2)$$

where $\overline{s(t)}$ is the sweep input into the ground. This equation can be simplified to

$$cc(t) = r(t) * k(t), \quad (3)$$

since the crosscorrelation of two identical sweeps is defined as a Klauder wavelet, $k(t)$. Crosscorrelation collapses the sweep to a Klauder wavelet at impedance contrasts and filters the data with the sweep parameters. The filtering of the data may be a problem if the sweep was improperly designed or if there were errors during acquisition.

Frequency domain sweep deconvolution

Frequency domain sweep deconvolution (FDSD) is based on the same convolutional model as crosscorrelation, however for simplification the equation is written in the frequency domain as:

$$X(\omega) = R(\omega)S(\omega). \quad (4)$$

The conversion into the frequency domain allows the processor to remove the sweep through division. The deconvolved trace is:

$$FDS D(f) = \frac{R(\omega)S(\omega)}{S(\omega)} \quad (5)$$

There are several advantages to this method. Through synthetic modelling it was determined that for noise free data, where the entire spectrum is covered by the sweep, a perfect answer for the reflectivity can be obtained. Another significant advantage of this method is that the spectrum is whitened, leaving no residual effects from the sweep. In crosscorrelation the sweep shape creates a filter whose spectrum is equal to sweep's power spectrum. The complete removal of the sweep for the swept frequencies is important as additional resolution may be obtained in the taper zone of the sweep. This creates the opportunity during field acquisition for increased tapers times to achieve the maximum amplitudes, and allows the inclusion of non-linear sweeps with no permanent effects on the seismic results.

There are several steps required for the removal of the sweep. If the sweep and trace are of different lengths they should be padded with zero values. Following this a Fourier transform is completed for both the trace and sweep. The trace is then divided by the sweep in the frequency domain to return the trace with no embedded sweep. Finally an inverse Fourier transform is completed on the new trace to calculate the time domain deconvolved trace.

Field data: Petro-Canada

The method of FDS D was tested on a data set acquired by Petro-Canada in 1999. The data was acquired with a linear 10-80 Hz sweep at a sample rate of 2ms and a sweep length of 16 seconds. The taper length both at the start and end is 300ms. The shot point interval is 25m and the geophone interval was 5m.

A direct comparison was made between crosscorrelation and FDS D by following identical processing sequences. Results from the synthetic modelling indicated that the noise outside of the sweep's frequencies would be amplified for FDS D. The amplification of the noise was substantially limited with the addition of a 1% stability factor. Any noise still remaining outside of the sweep frequencies was removed with a bandpass filter.

Both sweep removal methods generated similar results before any surface consistent deconvolution was completed. With the completion of the minimum-phase deconvolution process there was a small phase rotation of the crosscorrelated data. The comparative phase rotation between the two methods was determined to be 18.5 degrees.

Once the data was stacked, there were slight disparities for both the phase and resolution of the data. The phase difference is a result of the incorrect assumption of a minimum-phase embedded wavelet during minimum-phase surface-consistent deconvolution. The slight resolution differences can be attributed to the whitening of the amplitude spectrum in both FDS D and in the surface-consistent deconvolution. FDS D shows slightly better results with better continuity along the shallow reflections.

The main interest is the comparison of crosscorrelation and frequency domain sweep deconvolution to the real reflectivity. A synthetic from a nearby well can be tied to the seismic data to compare the results of crosscorrelation and FDS D. The well is located slightly off the line, however an excellent tie can be completed between the seismic and the synthetic. The synthetic was created with a 10-80 Klauer wavelet to replicate the ideal zero-phase result of the field data. The tie was made at the clastic/carbonate interface, the largest and most significant change in velocity and density. The results of this tie are shown in Fig. 1. There is some stretch associated with the seismic, which is expected due to the location of the well in comparison to the line.

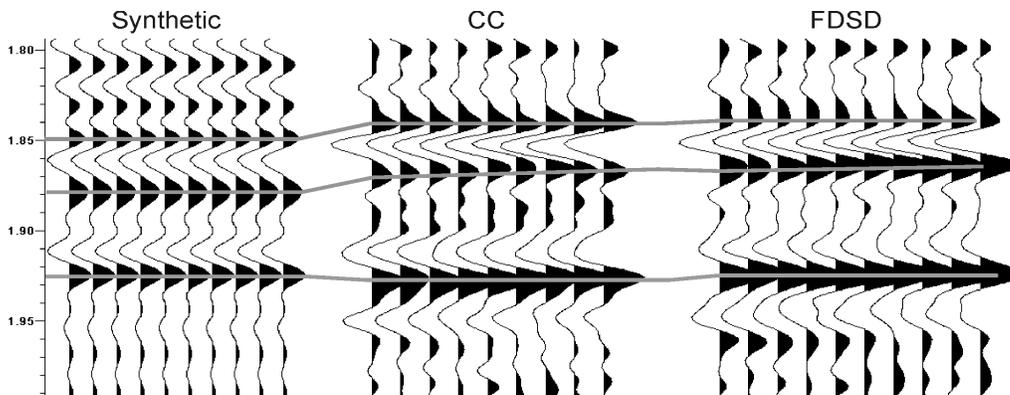


Fig. 1. A comparison of the well log synthetic, crosscorrelation and FDS D for the clastic to carbonate boundary. The two methods are compared to the synthetic data from a local well log indicating that the phase rotation is less significant for FDS D.

Both the methods of crosscorrelation and FDSO show slight dissimilarities compared to the synthetic data. The most significant difference between crosscorrelation and FDSO is at 1.90 seconds. The crosscorrelation result shows small doublets that are not visible on the synthetic; rather they show up as an increase in amplitude and become peaks. With a positive phase rotation these peaks can be recreated. Another significant difference is the wavelet shape for the lowest picked wavelet. The wavelet for crosscorrelation shows a slightly wider wavelet with a non-symmetrical shape compared to the synthetic data. This irregularity can be modelled if a 20-degree phase rotation is applied to the synthetic. A third comparison can be made at the top pick, where the result of FDSO is closer to the synthetic than crosscorrelation.

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